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13. ABSTRACT (Maximum 200 words)

FINAL PROGRESS REPORT-ABSTRACT

The accomplished research concerned the definition and development of a new wireless tactical network architecture that can reliably and efficiently support multimedia communication. This architecture, termed RAPID network, for ``Reliable, Available, high Performance Integrated multimedia Delivery" network, is characterized by the complete mobility of all nodes, limited bandwidth, large geographic areas, and large population of users. Networks with these characteristic are termed ad hoc networks, given their suitability for being used in an on-the-fly, ad hoc fashion.

This project accomplished major results in three core areas of research for RAPID networks, namely:

1) Novel clustering protocols that realize a two tier physical/logical network organization, that achieve scalability while minimizing the clustering overhead

2) Directional Routing, for robust and efficient routing of information throughout the network.

3) Virtual path design, to design scalable communication protocols for the RAPID architecture.

Beyond the publications of dozens of papers, this project involved faculty personnel and students whose career advanced as a result of participating in the accomplished research.

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FINAL PROGRESS REPORT

1. TITLE OF PROJECT: **A Reliable, Available, High Performance Integrated Multimedia Delivery (RAPID) Tactical Communication System**

2. GRANT NUMBER: **DAAG55-96-1-0382**

3. PERIOD COVERED BY REPORT: **1 January 1998–31 December 1999**

4. NAME OF INSTITUTION: **The University of Texas at Dallas**

5. PRINCIPAL INVESTIGATOR: **Imrich Chlamtac**

6. **Reliable, Available, high Performance Integrated multimedia Delivery (RAPID): Statement of the problem**

   The accomplished research concerned the definition and development of a new wireless tactical network architecture that can reliably and efficiently support multimedia communication in an environment characterized by high mobility of possibly all network nodes, limited bandwidth, large geographic areas, and large population of users. Networks with these characteristic are termed ad hoc networks, given their suitability for being used in an on-the-fly, ad hoc fashion.

   Termed RAPID network, for "Reliable, Available, high Performance Integrated multimedia Delivery" network, the proposed communication system is unique in concept and performance. Its name reflects the network's rapid deployment attribute and its ability to guarantee performance in face of rapidly moving mobile agents.

   RAPID introduces the concept of a two tier physical/logical network organization. It utilizes a novel, guaranteed-delivery, topology independent and efficient, TSMA (Time-Spread Multiple-Access) protocol to operate a secure and reliable "data-signalling" control channel in the mobile, multihop radio network. The provision of the reliable "control" channel, makes it in turn possible to construct, or superimpose, a highly available, controlled virtual cellular system in the mobile environment. Using wider, remaining, bandwidth for information transfer, the resulting cellular network can consequently reliably support voice, video and image transmission, while fully utilizing the "information" channel capacity in a tactical environment.

7. **Summary of the most important results**

   The research funded through the RAPID project lead to several breakthrough results which we believe will have a major and long lasting impact on mobile networks in general, and on ad hoc/tactical networks in particular. During this period we have developed novel solutions in three major areas of research, namely:

   (a) Hierarchical organization (clustering) to realize the two tier physical/logical network organization, which is the core concept to the RAPID architecture.

   (b) Directional Routing, for robust and efficient routing of information throughout the network.

   (c) Virtual path design, to design scalable communication protocols for the RAPID architecture.

In the following we give an overview of what it has been accomplished, and we list the resulting publications.

(a) **Clustering for the RAPID architecture** We started by introducing a Generalized Clustering Algorithm (GCA) for the efficient physical clustering of any ad hoc network (the nodes of the network are partitioned into clusters each with one clusterhead and ordinary nodes) and a Distributed GCA (DGCA) for clustering static multi-hop networks with limited knowledge of the network topology.

The DGCA has been enhanced to cope with the mobility of the nodes, both at *clustering set up* and for the *clustering maintenance* phase. Our research addressed both phases of the clustering process under the common perspective of some desirable clustering properties. Specifically, given the wireless, mobile nature of ad hoc networks, the need arises for each ordinary node 1) to have at least a neighboring clusterhead (this will allow fast communication among any pair of nodes), and 2) to be affiliated with the "best" neighboring clusterhead. Moreover, 3) we do not want to have neighboring clusterheads, so that the clusterheads are well scattered throughout the network.

Two algorithms have been introduced for the set up and the set up/maintenance of a clustering organization of any ad hoc network that have easy and efficient distributed implementations, and that satisfy the requirements described above.

The first algorithm, the *Distributed Clustering Algorithm* (DCA), is a common generalization of the GCA for which we have studied the time and message complexities, and discussed their optimality. In particular, we have proven for the first time that the time complexity of the DCA is bounded by a network parameter that depends on the network *topology* (that may change due to node mobility) rather than on the *size* of the network, i.e., the invariant number of its nodes.

The second algorithm is suited for (possibly highly) mobile networks and it is called *Distributed Mobility-Adaptive Clustering* (DMAC). By executing the DMAC routines, each node reacts locally to any variation in the surrounding topology, changing its role (either clusterhead or ordinary node) accordingly. The DMAC is proven to meet the three requirements of ad hoc clustering regardless of the mobility of the nodes, thus creating and maintaining the same clusters produced by the DCA. Moreover, for our algorithm, we obtain the following properties, not available in previous solutions:

- As for the [D]GCA, the selection of the clusterheads is based on the new weight-based criterion, thus having the possibility to express *preferences* on which nodes are better suited to be clusterheads.
- Nodes can move, even during the clustering set up. (DMAC is *adaptive* to the changes in the topology of the network, due to the mobility of the nodes or to node addition and/or removal.)
- A node decides its own role (clusterhead or ordinary node) knowing solely its current *one* hop neighbors (as opposed to the knowledge of one *and two* hop neighbors as required by previous algorithms).

Based on the proposed clustering algorithms, a reliable network backbone can be defined that spans over the clusterheads and it is mobility adaptive. Based on the well known theory of random graph, and through extensive simulations experiments, we have shown that the numbers of backbone nodes and links are consistently smaller than the corresponding numbers of nodes and links in the "flat" network topology. These numbers have been shown to grow polylogarithmically in the size of the network, which achieve scalability when implementing communication protocol over the backbone. Finally, additional results were published concerning the decrease in clustering maintenance overhead when a given number of clusterhead are allowed to be neighbors.

(b) **GPS-enabled Routing in RAPID architectures** Exploiting the commercial availability of Global Positioning Systems (GPS) devices, we have introduced a novel routing protocol based on a new definition of routing information. In our approach, the routing table stored at each node contains *location information* for any other node in the network (e.g., geographic coordinates that can be obtained by the use of GPS). When a node A wants to send a message m to a node B, it uses the location information for B to obtain B's *direction*, and then transmits m to all its one hop neighbors in the direction of B. Each neighbor repeats the same procedure, until B, if possible, is eventually reached.

Finding B in the computed direction, relies on how the location information is disseminated through the network. In our model, each node transmits control messages bearing its current location to all the other nodes. The frequency with which these control messages are transmitted is determined by:

- considering what we call the *distance effect*: The greater the distance separating two nodes, the slower they appear to be moving with respect to each other. Thus, nodes that are far apart, need to update each others locations less frequently than nodes closer together. This is realized by associating with each control message an "age" which corresponds to how far from the sender that message travels;
- the *mobility rate*: The faster a node moves, the more often it must communicate its location. This allows each node to self optimize its dissemination frequency, thus transmitting location information only when needed and without sacrificing the route accuracy.

Since distance and mobility play a central role in our protocol, we name it the *Distance Routing Effect Algorithm for Mobility* (DREAM) protocol for ad hoc networks. Due to the new definition of routing information, we do not have to exchange large amounts of control information as in existing protocols. At the same time, since no route discovery is needed, we do not suffer the associated delay typical of solutions that need to discover a route each time a message is to be sent. Furthermore, DREAM achieves the following desirable properties:

- it is *bandwidth and energy efficient*: Each control message carries only the coordinates and the identifier of a node, thus being small compared to the control messages used by other protocols to carry either routing tables or an entire route. Most importantly:
  - The rate of control message generation is determined and optimized according to the mobility rate of each node individually.
  - Due to the "distance effect" the number of hops (radius from the moving node) it will be allowed to travel in the network before being discarded will only depend on the relative (geographic) distance between the moving node and the location tables being updated.

  In this way the number of copies as well as the number of hops control messages will travel are both optimized (minimized) without sacrificing quality. This means that with respect to existing protocols, in DREAM more bandwidth and energy (required for transmission in each mobile node) can be used for the transmission of data messages;

- it is *robust*, meaning that the data message can reach its intended destination by following possibly independent routes;
- it is *adaptive to mobility*, since the frequency with which the location information is disseminated depends on the mobility rate.

Based on the efficient dissemination mechanism of location information, we published several papers on multipoint communication and route availability in RAPID networks. The basic idea associated to these papers is the following.

By adding to the location packets information regarding the current transmission range of each node, each node can maintain locally an "approximate snapshot" of the topology of the RAPID network as a *network topology graph* where there is an edge between two nodes when their distance is less than the minimum between their transmission radii. Having such representation of the nodes and links among them, each node can actually run a communication algorithm locally, and efficiently, compute the desired route(s) and piggyback the route so found to the message. In the case of routing, we obtained dynamic source routing that improves with respect to source routing proposed solutions since the route search phase is now not required. We were able to obtain significant results concerning multicast and broadcast too. For both problems, efficient algorithms can be locally run that compute Steiner and spanning trees that cover a multicast group of nodes and all the nodes, respectively. (In the case of multicast, of course, we use well-known heuristics for the Steiner tree problem, which is computationally hard.) Once it has computed the tree, a source node efficiently generate a coding of the tree whose length is linear in the number of the tree nodes, and piggyback it to the data packet. The proposed solution deploys the tree unique *Prüfer sequence*, thus requiring no extra space with respect to the routing case, when a source-destination route is piggybacked (a linear amount of space is required in this case as well). Simulation results show that for RAPID architecture made up of a limited number of nodes this algorithms achieve routing, multicast and broadcast with little overhead, low delay, and very low need to recur to flooding to deliver messages that cannot be delivered directly.

(c) The following research has been investigated in the field of designing the logical topology of a virtual path (VP) network, an important task in ATM network design that can be also exploited for RAPID-like architecture. We have introduced an algorithm that provides a VP network topology that is asymptotically optimal with respect to both connectivity and the diameter of the network. These optimality properties are combined with algorithmic simplicity and polynomial running time, thus overcoming the notorious "optimality vs. scalability" dilemma. This result is made possible by applying the theory of *random graphs* to this type of networks. This theory has the methodological advantage of increased accuracy with growing network size. Our work exemplifies that the theory of random graphs, beyond supporting analysis, may serve as a useful tool in the design of algorithms that overcome the "scalability bottleneck," a problem that prevents current approaches from finding near-optimal solutions as today's networks grow in size and complexity.

8. Published Papers and Delivered Speeches

The following is the list of the speeches given by the PI and of the peer-reviewed international journals and conferences where the papers produced under the "RAPID grant" were published.

- **S. Basagni I. Chlamtac A. Farago V. R. Syrotiuk, and R. Talebi**, "Route Selection in Mobile Multimedia Ad Hoc Networks," *6rd International Workshop on Mobile Multimedia Communications*, 1999.
- **I. Chlamtac, A. Farago, A.D. Myers, V.R. Syrotiuk, and G. Zaruba**, "ADAPT to Mobility," *IEEE Global Telecommunications Conference, GLOBECOM'99*, Rio De Janeiro, Brazil.
- **S. Basagni, I. Chlamtac, V. R. Syrotiuk and B. A. Woodward**, "A Distance Routing Effect Algorithm for Mobility (DREAM)," in *Proceedings of the Fourth Annual ACM/IEEE International Conference on Mobile Computing and Networking, MobiCom'98*, pg. 76–84, Dallas, TX, October 25–30, 1999.
- **S. Basagni, I. Chlamtac and V. R. Syrotiuk**, "Geographic Messaging in Wireless Ad Hoc Networks," in *Proceedings of the IEEE* 49*th Annual International Vehicular Technology Conference*, Houston, TX, May 16–20, 1999.
- **S. Basagni, I. Chlamtac and V. R. Syrotiuk**, "Dynamic Source Routing for Ad Hoc Networks Using the Global Positioning System," in *Proceedings of the IEEE Wireless Communications and Networking conference (WCNC'99)*, New Orleans, LA, September 21–24, 1999.
- **A. Faragó, I. Chlamtac and S. Basagni**, "Virtual Path Network Topology Optimization Using Random Graphs," in *Proceedings of IEEE INFOCOM'99. The Conference on Computer Communications*, vol. 2, pg. 491–496, New York, NY, March 21–25, 1999.
- **I. Chlamtac and A. Faragó**, "A New Approach to the Design and Analysis of Peer-to-Peer Mobile Networks," in *ACM/Baltzer Wireless Networks, n. 3*, vol. 5, May 1999.
- **S. Basagni**, "Distributed Clustering for Ad Hoc Networks," in *Proceedings of the 1999 International Symposium on Parallel Architectures, Algorithms and Networks (I-SPAN'99)*, Fremantle, Australia, June 23–25, 1999.
- **S. Basagni**, "Clustering for Multi-Hop Wireless Networks," in *Proceedings of the 1999 International Symposium on Wireless Communications (ISWC'99)*, Victoria, BC, Canada, June 3–4, 1999.
- **S. Basagni**, "Distributed and Mobility-Adaptive Clustering for Multimedia Support in Multi-Hop Mobile Wireless Networks," in *Proceedings of IEEE Vehicular Technology Conference (VTC) 1999, Fall, Gateway to 21st Century*, Amsterdam, The Netherlands, 19–22 September, 1999.
- **Y. Fang, I. Chlamtac and Y. Bing Lin**, "Modeling PCS Networks Under General Call Holding Time and Cell Residence Time Distributions," *IEEE/ACM Transactions on Networking*, Vol. 5, No. 6, December 1997.
- **I. Chlamtac, A. Faragó and H. Zhang**, "Time Spread Multiple Access (TSMA) Protocols for Multihop Mobile Radio Networks," *IEEE/ACM Transactions on Networking*, Vol. 5, No. 6, December 1997.
- **Y. Fang, I. Chlamtac and Y. Bing Lin**, "Call Performance for a PCS Network," *IEEE Journal on Selected Areas in Communications*, Vol. 15, No. 8, October 1997.

- **Y. Bing Lin and I. Chlamtac**, "A Model with Generalized Holding and Cell Residence Times for Evaluating Handoff Rates and Channel Occupancy Times in PCS Networks," *Intl. J. Wireless Info. Networks*, 4(3): 163–171, 1997.
- **I. Chlamtac**, "Wireless Access," Invited Speaker, in *International Zurich Seminars On Digital Communications*, February 1997, Zurich, Switzerland.
- **I. Chlamtac**, "Emerging Models for Mobile Communication Systems," Invited Talk, in *IFIP International Conference on the Performance and Management of Complex Communication Networks, PMCCN '97*, November 1997, Tsukuba, Japan.
- **T. Liu, V. Bahl and I. Chlamtac**, "A Hierarchical Position-Prediction Algorithm for Efficient Management of Resources in Cellular Networks," in *Proc. IEEE GLOBECOM'97*, Phoenix, Arizona, November 1997.
- **T. Liu, V. Bahl and I. Chlamtac**, "Aggressive Handoff Management in Third Generation Integrated Cellular Networks," *SPIE International Symposium on Voice, Video and Data Communications*, Dallas, TX, November 1997.
- **T. Liu, V. Bahl and I. Chlamtac**, "An Optimal Self-Learning Estimator for Predicting Inter-Cell User Trajectory in Wireless Radio Networks," *IEEE International Conference on Universal Personal Communications, ICUPC*, San Diego, CA, October 1997.
- **S. Basagni, I. Chlamtac and A. Faragó**, "A Generalized Clustering Algorithm for Peer-to-Peer Networks," *Workshop on Algorithmic Aspects of Communication*, (satellite workshop of ICALP 97) Bologna, Italy, 11–12 July 1997.
- **I. Chlamtac**, "Personal and Ubiquitous," Invited Talk, *The International Workshop on Mobile and Wireless Communications Networks*, Paris, France, May 1997.
- **V. Bahl, I. Chlamtac and A. Faragó**, "Optimizing Resource Utilization in Wireless Multimedia Networks," *The IEEE International Conference on Communications, ICC'97*, Montreal, Quebec, Canada, June 1997.
- **Y. Fang, I. Chlamtac and Y. Bing Lin**, "Channel Occupancy Times and Handoff Rate for Mobile Computing and PCS Networks," *IEEE Transactions on Computers*, Vol. 47, No.6, 1998.
- **T. Liu, V. Bahl and I. Chlamtac**, "Mobility Modeling and Location Tracking in Wireless ATM Networks," *IEEE Transactions on Communications*, Vol. 47, No. 7, July 1999.
- **V. Bahl, I. Chlamtac and A. Faragó**, "Resource Assignment For Integrated Services in Wireless ATM Networks," *International Journal of Communication Systems*, Special issue on Personal Communication Systems, John Wiley, (April 1998):29-41.
- **I. Chlamtac and J. Redi**, "Mobile Computing: Challenges and Opportunities," in *Encyclopedia of Computer Science, 4th Edition, International Thomson Publishing*, edited by David Hemmendinger, Anthony Ralston and Edwin Reilly, 1998.
- **S. Basagni, I. Chlamtac, and V. Syrotiuk**, "Location Aware Multicast for Mobile Ad Hoc Networks," to appear in *Computer Networks Journal.*
- **G. Zaruba, I. Chlamtac, and S. K. Das**, "An Integrated Admission-Degradation Framework for Optimizing Real-Time Call Mix in Wireless Cellular Networks," to appear in *ACM/Kluwer/SPIE Mobile Networks and Applications.*

- **S. Basagni, D. Bruschi, and I. Chlamtac**, "A Mobility Transparent, Deterministic Broadcast Mechanism for Ad Hoc Networks," *IEEE/ACM Transactions on Networking*, Vol. 7, No. 6, December 1999.
- **G. Zaruba, I. Chlamtac, and S. K. Das**, "An Integrated Admission-Degradation Framework for Optimizing Real-Time Call Mix in Wireless Cellular Networks," BEST PAPER, *ACM International Workshop on Modeling Analysis and Simulation of Wireless and Mobile Systems (MSWiM 2000)*, Boston, August 2000.
- **S. Basagni, I. Chlamtac, V. Syrotiuk, and R. Talebi**, "On-Demand Location Aware Multicast (OLAM) for Ad Hoc Networks," *IEEE the Wireless Communications and Networking Conference, WCNC*, 2000.
- **S. Basagni, I. Chlamtac, and V. R. Syrotiuk**, "Location Aware One-to-Many Communication in Mobile Multi-hop Wireless Networks," *IEEE Vehicular Technology (VTC)*, Tokyo, Japan, May 2000.

9. **Participating Personnel**

The following individual participated in the research activities under this grant.

(a) Imrich Chlamtac, PI

(b) Stefano Basagni. Dr. Basagni earned is Ph.D. degree in Computer Science while employed on the project

(c) Marco Monguzzi

(d) Xiaolin "Mark" Zhao